Northwestern University
Evanston, Illinois

HEAO-3 C-1 Observations of PSR1509-58 and PSR 0833-45

by

M. P. Ulmer and W. R. Purcell
Department of Physics and Astronomy, Northwestern Univ

and

W. A. Wheaton and W. A. Mahoney
JPL

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Abstract

We report upper limits to the 50 keV to 10 MeV gamma ray pulsations from PSR1509-58 and PSR0833-45 (Vela) made with the HEAO-3 C-1 experiment. The 2σ upper limit to the 50 to 300 keV flux from PSR1509-58 is 6.9×10^{-6} photons cm^{-2} s^{-1} keV^{-1}. This limit, combined with the previously measured X-ray flux, suggests that there is a break in the spectrum below $\sim$ 50 keV. This upper limit is not stringent enough, however, to distinguish between thermal and non-thermal models for the source of the X-ray emission from PSR1509-58. The 2σ upper limit to the 3.2 to 10 MeV flux from PSR0833-45 is 6.4×10^{-8} photons cm^{-2} s^{-1} keV^{-1}, consistent with the previous suggestion by Tümer *et al.* that the gamma ray flux from PSR0833-45 is variable.

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I Introduction

We report the analysis of 0.05 – 10 MeV observations made with the HEAO-3 C-1 experiment of the pulsars PSR1509-58 and PSR0833-45 (Vela). Although this instrument was not intrinsically more sensitive than the HEAO-1 A-4 experiment (Knight *et al.*, 1982), much more observing time on these two sources was obtained with HEAO-3 than with HEAO-1.

The pulsar PSR1509-58 has a period of $\sim$ 150 ms and a braking index of $\sim$ 2.8, slightly larger than that of the Crab pulsar (Manchester, Durdin, and Newton 1985). Comparing PSR1509-58 with the Crab pulsar, which has a braking index of $\sim$ 2.5 and produces a power-law X-ray and gamma-ray spectrum, PSR1509-58 could also be expected to produce a power-law spectrum. In fact, the observed $\sim$ 0.2 – 4.0 keV spectrum of PSR1509-58 is consistent with a power-law (Seward *et al.*, 1985; Seward and Harden, 1982), and a simple extrapolation suggested that it should have been detectable by HEAO-3 C-1. Futhermore, there is an $\sim 1\sigma$ hint that the source was detected above $\sim$ 100 MeV by COS-B and SAS-2 (see Simpson, 1980; Swanenburg *et al.*, 1981; Wills *et al.*, 1980; and Hermsen, 1980). A detectable $\gtrsim$ 100 MeV gamma-ray flux would suggest that the spectrum is non-thermal and that the X-ray flux might extend to higher energies at levels that would have been detectable by the HEAO-3 C-1 experiment.

In contrast to PSR1509-58, the Vela pulsar has been previously detected in the $\sim$ 1 MeV – 1 GeV range (Tümer *et al.*, 1985; Grenier, Hermsen, and Clear, 1988). Furthermore, the $\sim$ 1 – 300 MeV flux from the Vela pulsar has been found to be variable (Tümer *et al.*, 1984; Grenier *et al.*, 1988; Sacco *et al.*, 1990) with a reported 1 – 10 MeV high-state flux detectable by HEAO-3 C-1. The Vela pulsar is also interesting to study because, although it is as easily detected at $\sim$ 300 MeV as the Crab pulsar (see Simpson, 1980; Swanenburg *et al.*, 1981; Wills *et al.*, 1980; and Hermsen, 1980), its behavior at other wavelengths is very different

(Smith, 1986 and references therein). For example: 1) the radio, optical and gamma ray emission are all out of phase for the Vela pulsar and in phase for the Crab pulsar; 2) pulsed X-ray emission is observed from the Crab pulsar but is undetected for the Vela pulsar; and 3) the Vela pulsar frequently exhibits macro-jumps or glitches (Cordes *et al.*, 1988) which are not observed from the Crab pulsar.

Specific questions we address here are: 1) which model, thermal emission from a hot polar cap (Greenstein and Hartle, 1983) or non-thermal emission (e.g. incoherent synchrotron, Pacini, 1971), best describes the X-ray emission process from PSR1509-58; and 2) is the 1 – 10 MeV flux from the Vela pulsar variable, as suggested by the combined work of Sacco *et al.* (198?) and Trümer *et al.* (1984).

II Observations and Results

The HEAO-3 spacecraft was launched in September, 1979, and remained operational until ????, 1980. The spacecraft was spin stabilized with a period of $\sim$ 20 minutes. The field-of-view of the HEAO-3 C-1 experiment was aligned perpendicular to the spin axis of the satellite, and so performed continuous 360 degree scans of the sky. Generally, the spin axis of the satellite was pointed at the sun, but during the fall of 1979 and the spring of 1980 the spin axis was pointed toward the north galactic pole so that the experiment was scanning the galactic plane.

The HEAO-3 C-1 experiment consisted of 4 cooled high-purity germanium detectors with an energy range of 50 keV to 10 MeV (Mahoney *et al.* 1980). An active collimator defined a field-of-view of 30° FWHM at 1 MeV. The main detector events were processed using a 8192-channel analog-to-digital convertor and time tagged to 78.125 μsec relative to known universal time.

In order to optimize the signal-to-noise for our analysis, the data were selected based on the following environmental parameters: charged particle rate ≤ 2000 counts sec^{-1}, zenith angle $\leq 110°$ and McIlwain magnetic L parameter $\leq 3.4\ R_{\oplus}$. Further data selections were used to separately constrain the position of the pulsars in the detectors field-of-view. For PSR1509-58, which has been detected at 4 keV, we judged that a detection would most likely occur near 50 keV and so only data collected when the pulsar was within 20° of the center of the field-of-view were used. For the Vela pulsar, which has been most consistently detected above 10 MeV, we judged that the 1 to 10 MeV region was most likely to yield a detection, and so data collected when the pulsar was within 30° of the center of the field-of-view were included. These selection criteria resulted in effective observation dates for PSR1509-58 and the Vela pulsar of January 12 through April 6, 1980 and September 24, 1979 to May 31, 1980, respectively.

After being selected using the above criteria, the data were epoch-folded modulo the pulsar phase. The pulsar phase was calculated using the equation

$$\phi = \phi_0 + \nu_0(t - t_0) + \dot{\nu}_0\frac{(t-t_0)^2}{2} + \ddot{\nu}_0\frac{(t-t_0)^3}{6} \tag{1}$$

where ϕ_0, ν_0, $\dot{\nu}_0$, and $\ddot{\nu}_0$ are the pulsar phase, frequency, first time derivative, and second time derivative, respectively, at the reference epoch t_0, and t is the (barycenter corrected) photon arrival time. The values of ν_0, $\dot{\nu}_0$ and $\ddot{\nu}_0$ were obtained from the radio ephemerides of the pulsars (Downs and Reichley, 1983; Cordes, Downs, and Krause-Polstroff, 1988; Downs, 1982; Manchester, Durdin and Newton, 1985). The ephemerides used to produce the upper limits to the gamma ray flux from these pulsars are given in Table 1.

Estimating a flux from observed counts requires an assumption about the spectral index. Over the range of reasonable spectral indices, 1 to 3, the estimate of flux from observed counts varies by less than 10% (Mahoney *et al.*, 1981). For our analysis we have assumed a spectral index of 2. A detailed discussion of the analysis for each pulsar is given below.

II.1 PSR1509-58

Although there were some contemporaneous X-ray observations of PSR1509-58 (Weisskopf *et al.*, 1983), the resulting X-ray ephemeris was not accurate enough to determine the pulsar phase over the 60 day interval during which our data were accumulated. We therefore used the more accurate radio ephemeris of Manchester *et al.* (1985) measured in 1981 and 1982. Since the radio ephemeris is found to be consistent with the X-ray ephemeris, and there was no evidence of glitches in the radio data, we believe that the radio ephemeris provided the greatest accuracy in the determination of the pulsar phase over the interval during which our data were accumulated.

Since PSR1509-58 has a significant $\ddot{\nu}$, this term was included in the determination of the pulsar phase (Equation 1). The accuracy to which $\ddot{\nu}$ was determined, however, was marginal for our purposes. To properly estimate the pulsar phase, we searched for pulsations over a $\pm 3\sigma$ range of $\ddot{\nu}_0$ values from 1.8550×10^{-21} to 2.10392×10^{-21} s^{-3} in 50 equally spaced steps. These tests were performed in the 50 – 300 keV energy range to be as close as possible in energy to the previously reported X-ray flux. No statistically significant pulsations were found in these data as determined by either a simple χ^2 test for a constant flux versus pulse phase or by fitting the data with a cosine function. The largest excess was found for $\ddot{\nu}_0 = 1.99724 \times 10^{-21}$ s^{-3}, within $\sim 1.5\sigma$ of the value reported by Manchester *et al.* (1985). Using this value of $\ddot{\nu}_0$, we folded the data once more in the individual 8192 detector energy channels. We then accumulated the epoch-folded spectra into 5 broad energy bands to produce a compact set of upper limits. The results of the fits are given in Table 2. For completeness, we also searched for pulsations over the 1 to 10 MeV range at the ephemeridies based on the radio (Manchester *et al.*, 1985) and the X-ray (Weisskopf *et al.*, 1983) observations. No statistically significant emission was detected using either of these ephemeridies.

The results given in Table 2 suggest a possible detection in the 1 – 5 MeV range. Analysis of the spectra averaged over the high and low portions of the phase, however, indicate that the observed excess is consistent with the detector background spectrum. Such an effect is not surprising since multiple trials were performed to maximize the 50 – 300 keV excess. we conclude, therefore, that no pulse was detected. The results provided in Table 2, then, can be used to produce upper limits to the pulsed gamma ray emission from PSR1509-58, but converting the results in Table 2 to quantitative upper limits is somewhat subjective. Given that the results in Table 2 are based on the ephemeris that gave us the maximum signal, we judge that a valid estimate of the 2σ upper limit for a given enrgy bin is the flux amplitude given in Table 2 plus one standard deviation.

II.2 Vela Pulsar

Nearly continuous radio observations were performed over the interval during which the HEAO-3 C-1 observations of the Vela pulsar were performed. This was important since the Vela pulsar has been observed to exhibit significant timing glitches. No timing glitches were observed within $\sim$ 300 days of our observations. We used the ephemeris data of Downs and Reichley (1983) to determine the pulsar phase as a function of time. We then folded the HEAO-3 C-1 data modulo the derived phase law.

As was the case for PSR1509-58, we detected no statistically significant pulsations. In the case of the Vela pulsar, however, the phase and pulse shape are known (see Tümer *et al.*, 1984; Grenier *et al.*, 1988). With this information, the upper limits were determined using the equation

$$\sigma = \frac{f^{1/2}C^{1/2}}{AT\Delta E} \tag{2}$$

where

$$f = \frac{\beta}{1-\beta} \tag{3}$$

and β represents the pulsar duty cycle, which we took to be 0.12 from Sacco *et al.* (1990)

and Tümer *et al.* (1984), C represents the total number of counts observed, A is the net effective area, T is the length of the observation and ΔE is the energy range over which the data were accumulated. The upper limits for the Vela pulsar using the above equations are given in Table 3. Equation 2 yields upper limits that are within $\sim 10\%$ of those calculated using equation 3 from Sacco *et al.* (1990). The Sacco *et al.* (1990) formula assumes that there are a negligable number of counts in the phase bins assigned to the pulse. Note, that the true value of β may be as low as ~ 0.06, based on the Tümer *et al.* (1984) work, which lowers our upper limits and those of Sacco *et al.* (1990) by a factor of ~ 1.4.

III Discussion

As noted in Taylor and Stinebring (1986) and Michel (1982), there is no simple picture that describes how pulsars shine. The problem is complex and it is likely that several processes and regions are involved in producing the observed emission from a single pulsar (cf. Smith, 1986; Cheng, Ho, and Ruderman, 1986). Since there is no *a priori* reason why we should expect different pulsars to have the same regions radiating in the same proportions, inter-comparisons and searches for patterns may not lead to fruitful results. This is the best we can do, however, until we have a better understanding of pulsar emission.

As noted above, PSR1509-58 is both a radio and X-ray pulsar. The radio observations show that PSR1509-58 has a measurable breaking index similar to the Crab Pulsar, and the X-ray observations are consistent with a power law spectrum. As shown in Figure 1, the reported upper limits to the gamma ray flux from PSR1509-58 are not consistent with an extrapolation of the power-law observed in the X-rays. The extrapolated X-ray flux would also exceed the upper limit to the ~ 300 MeV flux reported from SAS-2 and COS-B (see Simpson, 1980; Swanenburg *et al.*, 1981; Wills *et al.*, 1980; and Hermsen, 1980). Unless the emission is variable, a break in the spectrum is required. Our data (Table 2, Figure 1) indicates that the break occurs between about 4 keV and 50 keV, and that the size of the break could be in the range of $\sim 0.5 - 1.0$. If, indeed, the PSR1509-58 spectrum does have a break of between 0.5 and 1.0 near 50 keV, then its spectrum would be similar to that of the Crab (Knight, 1983). One interpretation of the data, then, could be that the emission from PSR1509-58 is simply a scaled down version of the Crab pulsar (Pacini and Savlati, 1987). There are significant differences between the X-ray pulse shapes of these two pulsars, however. (Seward et al. 1985).

An alternative explanation assumes that high energy photons are produced in the PSR1509-58 system, but that absorption by a strong magnetic field prevents their escape. The inferred magnetic field strength of PSR1509-58 is $\sim 10^{13}$ gauss (Pacini and Salvati, 1987), which is strong enough to absorb photons $\gtrsim 1$ MeV (Daugherty and Harding, 1983). These high energy photons could also be absorbed by the polar cap, resulting in a hot polar cap which could produce significant quantities of X-ray (Greenstein and Hartle, 1983). As noted by Helfand *et al.* (1983), however, the model of Greenstein and Hartle requires a large (and therefore unlikely) temperature difference between the magnetic pole and equatorial regions of the neutron star. In the event that hot polar cap model is the correct model, our data suggest that measurements in the 4 to 20 keV range should reveal the characteristic steep fall of a thermal spectrum. Thus, while the spectrum of PSR1509-58 clearly steepens somewhere between 4 and 50 keV, whether the X-ray emission has a thermal or non-thermal origin remains an open question.

The Vela pulsar has shown to be very complex in its behavior at both gamma ray and radio energies (Grenier, *et al.*, 1988; Cordes *et al.*, 1988). To explain the observed fact that the radio, optical and gamma ray pulsations are all out of phase (see Grenier *et al.*, 1988; Smith, 1986 and references therein), Smith (1986) has proposed a model in which different portions of the pulsar surface and magnetosphere are responsible for the pulses seen in these energy ranges.

The relatively frequent macro-jumps and micro-jumps open the possibility for searching for a relationship between gamma emission and the timing phenomena. Of course, this also means that Vela is a poor clock and requires a very accurate ephemeris when searching for pulsations over long data sets such as the one used here. The Vela pulsar was not observed to glitch (perform a macro-jump) during or within $\sim$ 300 days of our observations (Cordes *et al.*, 1988; Downs and Reichley, 1983).

The Vela pulsar was observed to be in a high state during the COS-B observations made in 1976, 1977, and 1981 (Grenier *et al.*, 1988), consistent with the assumption that it was in a high state when observed at lower gamma ray energies by Tümer *et al.* (1984) during a balloon flight in 1981. Whether or not the Vela pulsar was in a high state at 300 MeV during our entire 1979-1980 observations is not known, but Grenier *et al.* (1988) report a low flux near the end of 1979. The pulsar certainly could have been in a low state, which is consistent with our data and with the hypothesis that high states in the $\sim 1 - 10$ MeV energy range only follow glitches.

Since two groups (Sacco *et al.*, 1990 and the present work) failed to detect the pulsar at low levels, confirmation of Tümer *et al.* (1984) result is required before one can safely conclude that the Vela pulsar is variable in the $1 - 10$ MeV energy range.

We concur with the conclusions of Grenier *et al.*, (1988) and Smith (1986, and references therein) that this pulsar probably has several emission regions. Assuming the validity of both our results and those of Sacco *et al.* and Tümer *et al.*, we suggest that the region responsible for the bulk of the $1 - 300$ MeV gamma ray emission is unstable, causing the observed variability. Furthermore, the dearth of X-ray emission from the Vela pulsar could be related to the instability of the region that is emitting the $\sim 1 - 300$ MeV emission. In contrast, the Crab pulsar X-ray and gamma ray flux seem quite stable (Mahoney *et al.*, 1984; Knight, 1983), and the (presumably) non-thermal pulsed X-ray emission from the Crab pulsar could be related to the stability of its 1 – 300 MeV emitting region. This hypothesis suggests that monitoring the Vela pulsar in the X-ray region may yet lead to a detection, and that it is important to have simultaneous monitoring of the 1 – 300 MeV flux. NASA's Gamma Ray Observatory will provide the latter capability.

IV Summary and Conclusions

We have presented upper limits to pulsed emission from the pulsars PSR1509-58 and PSR0833-45. In the former case our limits, combined with previous X-ray detections, suggest that there is a break in the spectrum between $\sim$ 4 keV and 50 keV. We cannot, however, distinguish between the thermal and non-thermal hypotheses for the origin of the X-ray emission. Based on the current data, both are still equally likely and 4 to 40 keV observations are needed to choose between these two hypotheses. The upper limits to the pulsed emission from the Vela pulsar are inconsistent at the $\sim 3\sigma$ level with the reported detection of Tümer *et al.* (1984). The simplest explanation is that emission region responsible for the $\sim$ 1 – 300 MeV emission is unstable (Grenier *et al.*, 1988), although the lack of a detection by Sacco *et al.* (1990) as well as by us leaves open the possibility the Tümer *et al.* (1984) result is in error. Taking all the Vela results at face value, we suggest that the instability of the region on the Vela pulsar responsible for the 1 – 300 MeV emission may be related to the lack of detectable pulsed X-ray emission from this source.

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Table 1: **Pulsar Ephemerides**

Pulsar	t_0 **(Julian day)**	ν_0 (s^{-1})	$\dot{\nu}_0$ ($\times 10^{-11}$ s^{-2})	$\ddot{\nu}_0$ ($\times 10^{-21}$ s^{-3})
PSR1509-58	2,445,144.7437	6.656424796	−6.82427	1.99724
PSR0833-45				

Table 2: **Limits to Gamma Rays from PSR1509-58**

Energy Range (MeV)	**Best Fit Intensities**[1]
0.05 – 0.3	4.8 ± 2.1
0.3 – 0.5	0.1 ± 1.8
0.5 – 1.0	0.2 ± 1.4
1.0 – 5.0	1.3 ± 0.4
5.0 – 10.0	0.1 ± 0.2

Notes ________.

1. The intensities are based on a cosine fit to the data. The units are 10^{-6} photons cm^{-2} s^{-1} keV^{-1}. These are not considered to be statistically significant; see text for details.

Table 3: Limits Gamma Rays from the Vela Pulsar

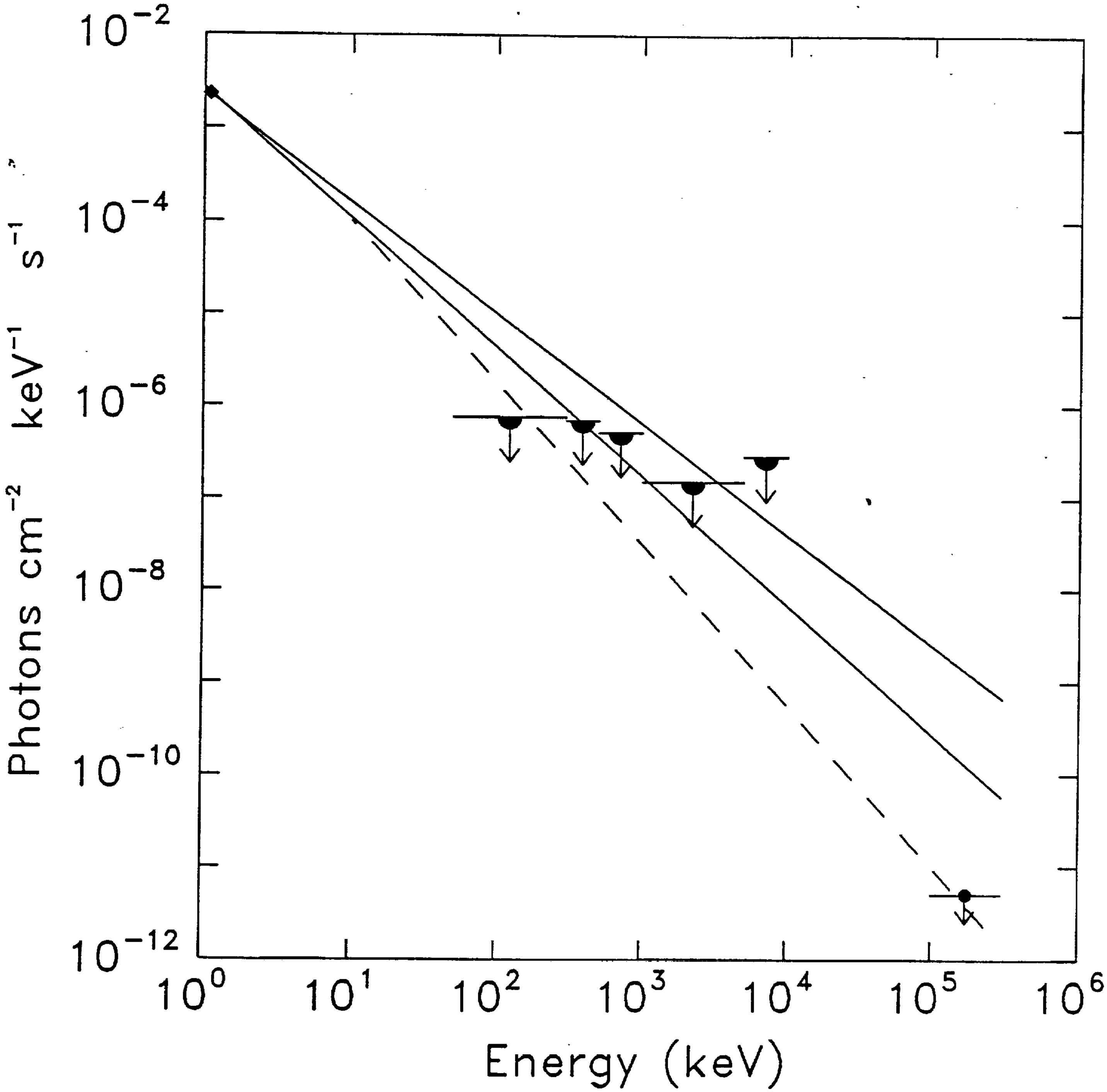
Energy Range (MeV)	Upper Limit[1]
0.05 – 0.1	1.4
0.1 – 0.4	0.93
0.2 – 0.4	0.38
0.4 – 0.8	0.33
0.8 – 1.6	0.16
1.6 – 3.2	0.79
3.2 – 10.0	0.032

Notes ________.

1. The upper limits are based on formula (2) of text. The units are 10^{-6} photons cm^{-2} s^{-1} keV^{-1}.

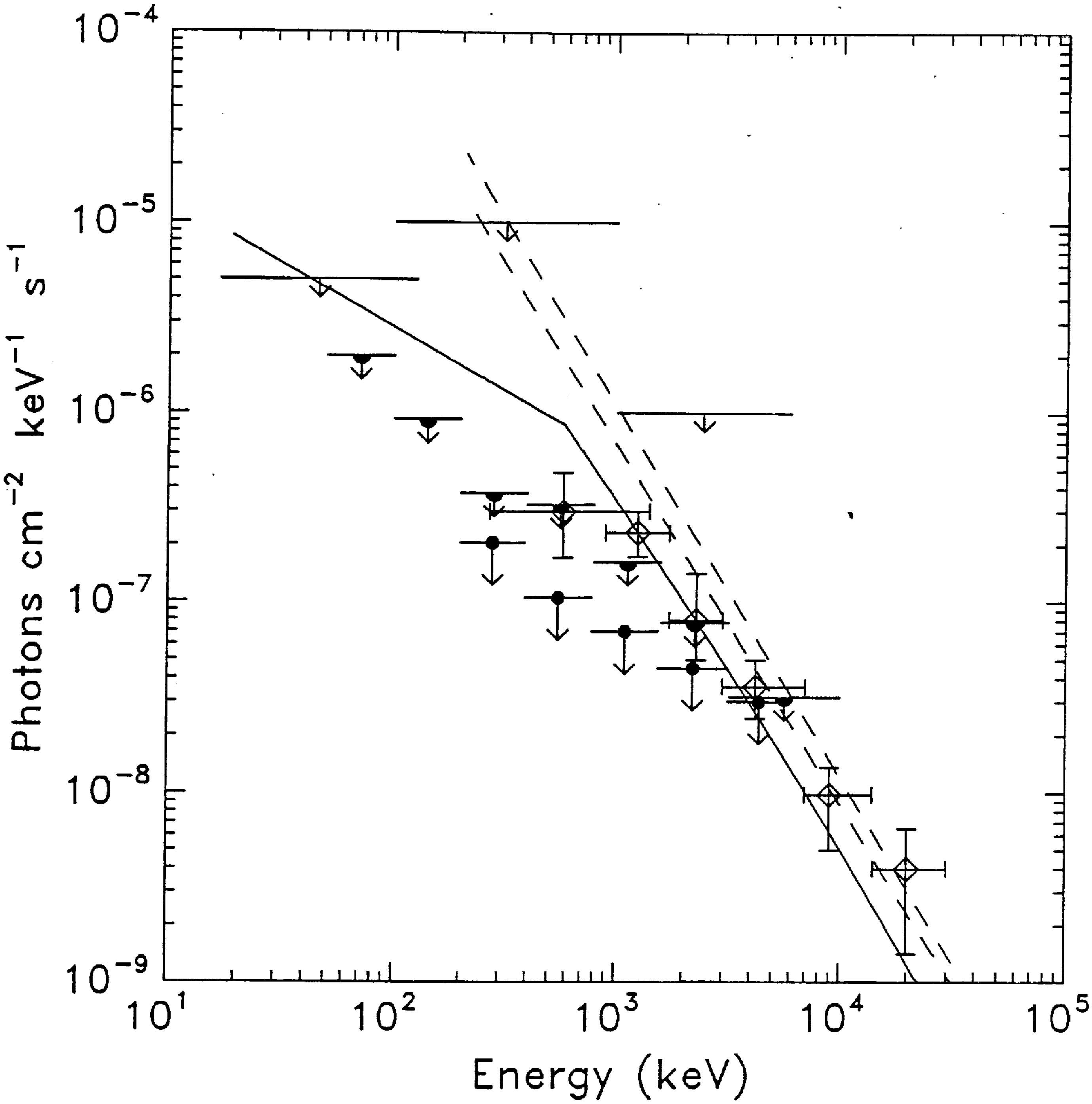
Figure 1. X-ray and gamma-ray measurements of PSR1509-58. The 50 keV - 10 MeV 2σ upper limits are the current work. The diamond in the upper left is the measured X-ray flux (Seward *et al.*, 1985). The 2σ upper limit in the lower right is based on the quoted sensitivity of COS-B (Hermsen, 1980; Simpson, 1980; Swanenburg, *et al.*, 1981). The solid lines represent the power laws for the best fit and the steepest model consistent with the X-ray data. The dashed line was generated by taking the 10 keV point from the extrapolated steepest X-ray model and connecting it to the sensitivity/upper limit point at 300 MeV.

Figure 2. Gamma-ray measurements of PSR0833-45. The open and closed diamonds are from Tümer *et al.* (1984). The dashed lines are the extrapolated spectra from the data of Lichti *et al.* (1980) with spectra indices of 1.9 and 2.0, coupled with the best fit intensity and the 1σ sensitivity normalization, respectively. The 2σ upper limits of the present work (half circles) and those of Sacco *et al.* (1990, full circles) are shown along with the 3σ upper limits given by Knight *et al.* (1980). The theoretical spectrum (solid curve) is based on the model of Cheng, Ruderman, and Ho (1986), with $\omega_{min} = 576$ keV.



10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
Photons cm^{-2} keV^{-1} s^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
Energy (keV)

Figure 1



10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
Photons cm^{-2} keV^{-1} s^{-1}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Energy (keV)

Figure 2